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The Mirage of the Fermi Scale

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The discovery of a light Higgs boson at LHC may be suggesting that we need to revise our model building paradigms to understand the origin of the weak scale. We explore the possibility that the Fermi scale is not fundamental but rather a derived one, i.e. a low energy mirage. We show that this scenario emerges in a very natural way in models previously used to break the electroweak symmetry dynamically and suggest a simple dynamical framework for this idea. In our model the electroweak scale results from the interplay between two very high energy scales, one typically of the order of \( \Lambda_{UV} \sim 10^{16} \) GeV and the other around \( M_W \sim 10^{10} \) GeV, although other values are also possible.


It is widely believed that the Fermi scale \( F_{\text{weak}} \approx 246 \) GeV is a fundamental one. This assumption has driven model builders efforts for the past decades. This scale underlies the masses of the weak gauge bosons via the time-honored relation

\[ 2 m_W = g F_{\text{weak}}, \tag{1} \]

where \( m_W \) is the mass of the W-boson and \( g \) is the weak coupling constant. If we neglect Quantum Chromodynamics (QCD), every other scale in the Standard model (SM) is related to \( F_{\text{weak}} \). The QCD scale arises purely from interactions and must be fit to experiments, for example, to the proton mass. By copying QCD one can naturalize the Fermi scale by replacing the SM Higgs sector with a new strongly coupled theory, and claiming that this technicolor dynamics generates the Fermi scale in analogy with \( \Lambda_{QCD} \) of ordinary strong interaction.

The discovery of the Higgs particle [1, 2], and confirmation of its properties, has impeded several model (in)dependent studies of the properties of the observed scalar [3-6]. An interesting further implication of the Higgs mass value \( m_h \approx 125 \) GeV arises from the stability analysis of the Higgs potential: Assuming no new physics beyond the SM, the Higgs potential flattens out and the quartic coupling becomes negative around \( \Lambda_{UV} \sim 10^{10} \) GeV. In other words, if no new physics exists beyond the SM, we might live in a metastable universe [7,9]. The correct implementation of the Weyl consistency conditions for the perturbative renormalisation group computations needed to determine the SM vacuum stability appeared in [9]. Despite all these developments, we still face the puzzle: What is the origin of the electroweak scale per se?

One logical possibility is that the Fermi scale is not a fundamental one but derived via an interplay of higher scales; de facto a low energy mirage. We will explore this possibility within natural extensions of the SM, constructed as a direct generalization of the composite Higgs and Unparticle \([10, 11]\) scenario introduced first in [12]. The scenario which we consider is reminiscent of the walking (extended) technicolor: We consider a strongly interacting gauge theory whose matter content is tuned so that the theory lies inside the conformal window. In other words the long distance behavior of the theory is governed by an infrared fixed point at scales \( \mu \leq \Lambda_{UV} \). The strongly interacting sector is coupled to the SM matter fields by extended gauge interactions, which are broken at high scale \( M_U \). What is essential in our case is that these extended technicolor interactions provide explicit breaking of the scale invariance and may perturb the theory slightly away from the conformal window. We will show that this breaking, when relevant below the scale \( \Lambda_{UV} \), leads to the emergence of an infrared scale which we identify with the Fermi scale, \( \Lambda_{IR} \sim F_{\text{weak}} \). Between the scales \( \Lambda_{IR} \) and \( \Lambda_{UV} \), the dynamics is similar to walking technicolor with large anomalous dimension of the techniquark bilinear. Due to approximate scale invariance below the scale \( \Lambda_{UV} \) the electroweak scale remains stable [13]. We assume that \( \Lambda_{UV} \leq M_U \) but allow also \( \Lambda_{UV} \ll M_U \).

In more detail, we first replace the unnatural Higgs sector of the SM with a natural strongly coupled non-supersymmetric gauge theory whose coupling flows to a nonperturbative infrared (IR) fixed point around the scale \( \Lambda_{UV} \), higher than the Fermi scale \( F_{\text{weak}} \). This means that we choose the number of technifermions, gauge group and matter representation in order to be within the conformal window [14]. We call the resulting theory Untechnicolor. Below the scale \( \Lambda_{UV} \) the Untechnicolor sector becomes conformal. Once coupled to the
electroweak gauge currents of the SM we expect small corrections \cite{15} which we neglect here. Another sector is responsible for the generation of the masses of SM fermions and pseudo Goldstone bosons (if present in the theory), and we consider this to be similar to extended technicolor: There exists gauge interactions connecting ordinary matter fields and untotechnicolor matter, but these gauge interactions are broken at mass scale $M_{U}$. At scales below $M_{U}$, these interactions are summarized via the following dimension six operators:

$$\begin{align*}
\alpha \frac{\bar{Q}Q \bar{Q}Q}{M_{U}^{2}} + \beta \frac{\bar{\psi} \psi \bar{Q}Q}{M_{U}^{2}} + \eta \frac{\bar{\psi} \psi \bar{\psi} \psi}{M_{U}^{2}},
\end{align*}$$

(2)

where $\alpha, \beta$ and $\eta$ coefficients parametrize our ignorance of the more fundamental theory. The field $Q$ denotes an untotechnicolor fermion, $\psi$ denotes a SM fermion and to keep the notation simple we have only considered one generation of SM fermions. The $\eta$-terms may induce, depending on the underlying dynamical structure, flavor changing neutral current interactions. However, we will consider very high energy values of $M_{U}$ effectively depleting any potentially dangerous flavor changing neutral current operators.

To illustrate the mechanism, we consider two Dirac techniflavors $U$ and $D$ belonging to some complex representation $R$ of a generic gauge group and gauged under the electroweak group. We consider the ultraviolet (UV) operator $O_{UV} = U_{R} R U_{L} + D_{R} D_{L}$ of this theory, where left- and right-handed techniquarks have usual charge assignments under the electroweak gauge group. Below the scale $\lambda_{UV}$ the Untechnicolor sector develops a nontrivial strongly interacting IRFP described by the Lagrangian $L_{CFT}$ and due to dimensional transmutation we have

$$O_{UV} \rightarrow \lambda_{UV}^{\gamma} O_{U}.$$  \hspace{1cm} (3)

Here $\gamma$ is the anomalous dimension of the techniquark mass operator and $O_{U}$ has dimension $d = 3 - \gamma$. Neglecting the small effects of the SM interactions, only the first term in Eq. (2) is relevant for the low energy effective Lagrangian

$$L_{CFT} + a \frac{\lambda_{UV}^{2\gamma}}{M_{U}^{2}} |O_{U}|^{2} = L_{CFT} + \frac{\tilde{a}}{2} |O_{U}|^{2},$$

(4)

where $\tilde{a} \equiv 2 \alpha \lambda_{UV}^{2\gamma} / M_{U}^{2}$. This last operator can drive the theory away from conformality \cite{12} as it becomes relevant if $\gamma$ is larger than one.

Without explicit mass terms, the Untechnicolor sector features a continuous mass spectrum. In order to deal with this spectrum we use the formalism introduced in \cite{16} amounting to consider, instead of the operator $O_{U}$, an infinite tower of canonically normalized massive scalar states $\phi_{k}$, $(k = 1, 2, ..., \infty)$, i.e.

$$O_{U} \rightarrow O = \sum_{k=1}^{\infty} f_{k} \phi_{k}.$$  \hspace{1cm} (5)

Here, $f_{k}^{2}(M_{k}^{2}) = \frac{B_{k}}{2\pi} \Delta^{2}(M_{k}^{2})^{d-2}$ where

$$B_{k} = \frac{16\pi^{5/2}}{(2\pi)^{2d}} \Gamma(d + 1/2) \Gamma(2d),$$

(6)

and the scalar fields $\phi_{k}$ are characterized by the mass squared $M_{k}^{2} = k \Delta^{2}$ as $\Delta \rightarrow 0$. Substituting this in Eq. (4) and taking into account also the mass terms of the fields $\phi_{k}$, the equation of motion determining the average value $\langle \phi_{n} \rangle$, and hence also the condensate $\langle O \rangle$, reads

$$\tilde{a} f_{n} \sum_{m=1}^{\infty} f_{m} \langle \phi_{m} \rangle = \tilde{a} f_{n} \langle O \rangle = M_{n}^{2} \langle \phi_{n} \rangle.$$  \hspace{1cm} (7)

Since $\langle O \rangle$ is independent of $n$, this equation implies that $\langle O \rangle \equiv c/\tilde{a}$, where $c \equiv M_{n}^{2} \langle \phi_{n} \rangle / f_{n}$ is a constant. Performing the limit $\Delta \rightarrow 0$ introduces UV and IR cutoffs defining the physical range where the effective Untechnicolor description holds. In our case an ultraviolet cutoff is $\Lambda_{UV}$ since above this scale the description in terms of the composite operator $O_{U}$ is no longer valid. The scale $\Lambda_{IR}$ is induced due to the presence of the relevant $a$-coupling in Eq. (1) which breaks the conformal symmetry, and this infrared scale $\Lambda_{IR}$ is identified with the constituent fermion mass, i.e. the condensate $\Lambda_{IR} \sim m_{const} \sim \langle O \rangle^{1/d}$. The result of the $\Delta \rightarrow 0$ limit is

$$\langle O \rangle = \frac{B_{U}}{2\pi} \Omega(\Lambda_{IR}, \Lambda_{UV}),$$  \hspace{1cm} (8)

where

$$\Omega(\Lambda_{IR}, \Lambda_{UV}) \equiv \int_{\Lambda_{IR}^{2}}^{\Lambda_{UV}^{2}} d\lambda^{d-3}.$$  \hspace{1cm} (9)

The above equations lead to the constraint

$$c = \frac{c}{\tilde{a}} \Rightarrow \frac{c}{\tilde{a}} \Omega(\Lambda_{IR}, \Lambda_{UV}) \equiv \frac{B_{U}}{2\pi} \Omega(\Lambda_{IR}, \Lambda_{UV}) = 1.$$  \hspace{1cm} (10)

Using the definition of $\tilde{a}$ and working in the range $1 < \gamma < 2$, Eq. (10) leads to the relation

$$\Lambda_{IR} \approx \Lambda_{UV} \left[ 1 + \pi^{\gamma - 1} \frac{M_{U}^{2}}{\Gamma(\gamma)\Gamma(2d)} \right]^{1/\gamma}.$$  \hspace{1cm} (11)

This is the advertised result of the emergence of the electroweak scale $\Lambda_{IR} \sim F_{weak}$ as a result of the interplay of higher energy physical scales.

In Fig.1 we plot Eq. (11) in $(\gamma, \Lambda_{UV})$ plane fixing $\Lambda_{IR} = 250$ GeV and $a = 0.5$ (we expect $a$ to be of order one). The different curves correspond to $M_{U} = 10^{16}$
from Fig. 1, Λ restraint in Eq. (10) translates to increased tuning of the coefficient.

Having assumed (dashed red) and MUV (solid black), MU = 10^{12} GeV (dotted blue). The electroweak scale emerges for quasi-conformal theories corresponding to these contours. Moreover, as Fig. 1 implies, for given scales ΛUV and MU, two solutions exist. One of these corresponds to γ ≈ 2 which mimics an elementary SM-like scalar Higgs. It is worth discussing this limit in more detail. Since BU → 0 as γ → 2 (see Eq. (6)) and α is expected to be of order one, Eq. (11) becomes

\[ \frac{[\Lambda_{UV}]}{\Lambda_{IR}} \approx \frac{1}{B_u} \left( \frac{M_U}{\Lambda_{UV}} \right)^2, \quad (γ ≈ 2). \]

Having assumed ΛUV ≪ MU and without fine-tuning BU we observe that the hierarchy between ΛIR and ΛUV Eq. (12) derives from a seesaw-like mechanism ΛIR ∼ ΛUV/MU. In Fig. 1 when approaching γ = 2 from below a curve corresponding to fixed values of MU and ΛIR, this scaling relation corresponds to the reach of the plateau at the maximum possible value of MU/ΛUV. For example, for the solid black curve corresponding to MU = 10^{16} GeV this happens for log(MU/ΛUV) ∼ log(MU/ΛIR)^1/2 ≈ 15 which translates into ΛUV ∼ 3 \times 10^9 GeV. At smaller values of MU/ΛUV, the plateau extends to the region ΛUV ≈ MU with increased tuning of the coefficient BU → (ΛIR/ΛUV)^2.

At the lower limit, γ ≈ 1, Eq. (9) reduces to Ω(ΛIR, ΛUV) = log(ΛUV/ΛIR)^2 and therefore the constraint in Eq. (10) translates to

\[ Λ_{IR} = Λ_{UV} \exp \left[ -\frac{π}{aB_u} \right], \quad (γ ≈ 1). \]

where we have replaced ā with a because, as is clear from Fig. 1, ΛUV ≈ MU in this limit and therefore ā ≈ a.

We thus see that in this limit the model features only one high energy scale, ΛUV, and the dynamically generated infrared scale ΛIR is exponentially suppressed with respect to ΛUV.

We have considered a model where all beyond SM dynamics occurs at very high scales and the EW symmetry breaking, hence the Fermi scale itself, emerges as a low energy mirage. In addition to giving a novel explanation for the existence of the Fermi scale, the model also provides further phenomenological implications which we will now discuss. Let us start with the top mass. In the limit γ ≈ 2 and MU = ΛUV it can be generated with the β-term in Eq. (12):

\[ \frac{\Lambda_{UV}}{M^2_{U}} \Rightarrow m_t \sim \frac{(O_U)_{M_U}}{M^2_U}, \quad (14) \]

where (O_U)_{M_U} condensate is evaluated at the scale MU. The large value of the anomalous dimension enhances the value of the condensate at high energy and for γ = 2 we have

\[ \frac{(O_U)_{M_U}}{(O_U)_{M_I}} = \frac{(M_U)}{(M_I)}^{γ ≈ 2}. \]

Using that (O_U)_{ΛIR} ∼ ΛIR^3 we obtain mt ∼ ΛIR in agreement with experiments.

Generating the large top mass becomes progressively more difficult when the hierarchy between ΛUV and MU grows. Assuming QCD-like running behavior between scales MU and ΛUV leads to (O_U)_{MU} ∼ (O_U)_{ΛUV} and therefore

\[ m_t \sim \left( \frac{Λ_{UV}}{M_U} \right)^2 Λ_{IR}. \]

Thus, additional contributions are needed below the flavor scale MU in order to bring the top quark mass to its experimental value. To extend the present context we may imagine a conformal topcolor scenario where relevant perturbations of the scale invariance at ΛUV would lead to both the electroweak scale and the top mass itself dynamically at low energies. We do not attempt a detailed solution of this idea here.

The phenomenology of these kind of models is similar to the one of ideal walking technicolor [18, 19] where chiral symmetry breaking (and therefore conformality) is driven by four-fermion operators. In this scenario, if the conformal transition is walking and not jumping, [20][21], we expect the models to feature a compressed tower of composite states at the induced electroweak scale, [22][23]. For behaviors at finite temperature, see [26]. The collider phenomenology of these models, expected to carry over to the present idea, has been investigated in [27][28]. Another important issue that any dynamical mechanism faces is how to obtain naturally (i.e. without invoking special dynamics) the correct physical mass.
of the composite Higgs state. The answer to this important point has been recently put forward in [29] and relies on the fact that the observed physical mass of the composite Higgs is due to the interplay of the composite dynamics and the corrections due to the coupling to the top (yet another four-fermion induced operator) which tends to lower the composite Higgs mass towards the observed value. Disentangling ideal walking from the models put forward here (technically an extreme case of ideal walking) requires stronger constraints on the new flavour physics scale and the knowledge of the detailed spectrum at the electroweak scale.

Till now we assumed that the gauge dynamics and the associated conformal breaking occurred via natural theories, i.e. gauge theories with only fermionic fundamental matter fields. The point we have proven is that the interplay of several natural fundamental sectors at very high energy can lead to the existence of the substantially lower electroweak scale.

Before concluding we would like also to speculate on the effects of the introduction of further irrelevant operators on near conformal dynamics. These operators, as we shall argue, might be useful for the generation of neutrino masses. To illustrate the mechanism we consider a toy construction making use of fundamental scalars, although the scenario could be later replaced by a more fundamental dynamics. Consider a SM-singlet complex scalar field $S$ and further assume that $S$ acquires a vacuum expectation value (vev) $\Sigma$. The lowest dimension-8 operator coupling $S$ with $O_{\text{UV}}$ is the following:

$$\kappa |S|^2 |O_{\text{UV}}|^2 / M_{U}^4,$$

where $\kappa$ is a dimensionless coupling constant of $O(1)$. After the SM-singlet scalar $S$ acquires a vev, we arrive at the following effective Lagrangian density

$$L_{\text{CFT}} + \frac{1}{2} \tilde{a}_{\text{eff}} |O_{\text{UV}}|^2,$$

where $\tilde{a}_{\text{eff}} = 2(\alpha + \kappa \frac{\Sigma^2}{M_{U}^2}) \frac{\lambda_{\text{UV}}}{M_{U}^4}$ and $\alpha$ and $\kappa$ are dimensionless couplings expected to be of $O(1)$. For $\kappa = 0$ we recover Eq. (4).

The Lagrangian of Eq. (18) has the same form as Eq. (4) with $\tilde{a} \to \tilde{a}_{\text{eff}}$ and, for $\kappa > 0$, $\tilde{a}_{\text{eff}} > \tilde{a}$. The addition of the complex scalar therefore increases the strength of the operator that drives the theory away from conformality. For this effect to be non-negligible it must be that $(S) = \Sigma \approx M_{U}$.

Within this setting now, consider the Yukawa sector for the neutrino sector of the SM, introducing also right handed neutrinos:

$$L_{\text{Yuk}} = - y_L O_{i} \nu_R^c \nu_R^c + \lambda S \nu_R^c \nu_R^c + h.c.,$$

where $L_L$ is the usual SM lepton doublet and $\nu_R$ is the right handed neutrino, $S$ and $O_{i}$ are the SM singlet scalar and low energy composite Higgs fields. The usual Yukawa coupling leading to Dirac mass is denoted by $y$ and the coupling leading to Majorana mass is $\lambda$. As the singlet $S$ condenses, a Majorana mass $M = \lambda \Sigma \sim M_{U}$ is generated, which is much greater than the value of the condensate $|O_{i}| \sim \lambda_{\text{UV}}^2 / M_{U}^2 \sim F_{\text{weak}}$ which generates a Dirac mass $m_{D} \sim y F_{\text{weak}}$. Therefore we obtain the conventional type-I seesaw mass matrix for the neutrinos which gives two physical Majorana eigenstates. First, a superheavy state with mass $m_{1} \sim M_{U}$ and an extremely light state with mass

$$m_{2} \sim \frac{y^2 \lambda_{\text{UV}}^4}{\lambda M_{U}^4} \sim \frac{y^2 F_{\text{weak}}^2}{\lambda M_{U}}. \quad (20)$$

Hence, we can explain the existence of the hierarchical scales observed in nature: the high scale $M_{U} \sim 10^{16-19}$ GeV, which sources the breaking of the scale invariance of the postulated new physics underlying the observed scale of the SM, the electroweak scale $F_{\text{weak}} = 246$ GeV and the sub-eV scale of neutrino masses $m \sim 10^{-2}$ eV. For alternative model setups of this type, see e.g. [30]. Among the new features is the existence and use of an intermediate scale $\Lambda_{\text{UV}} \sim 10^{10}$ GeV, also implied from the stability analysis of the SM with the observed Higgs sector.

To summarize, we have considered the possibility that the electroweak scale emerges via the interplay between two higher energy physical scales. As a concrete example, we considered a model framework consisting of a theory possessing a nontrivial IRFP at scales below $\Lambda_{\text{UV}}$ but perturbed by a four fermion coupling. We assumed that such coupling originates from a more complete theory above the scale $M_{U} \geq \Lambda_{\text{UV}}$. The resulting dynamics below the scale $\Lambda_{\text{UV}}$ is unparticle-like, and we termed it Untechnicolor. Assuming that the value of the four-fermion coupling is sufficiently large to enforce the dynamical vacuum expectation value for the scalar Untechnicolor operator, we demonstrated how the electroweak scale, i.e. $246$ GeV, identified with $\Delta_{U}$ arises. Below the electroweak scale the Untechnicolor sector turns into an effective SM Higgs-like sector.

Our construction explains how the electroweak scale arises due to small explicit breaking of scale invariance and how the electroweak scale is stable under radiative corrections due to approximate scale invariance below the compositeness scale $\Lambda_{\text{UV}}$. Furthermore, in the scenario we considered, the flavor physics scale can be around the compositeness scale $\Lambda_{\text{UV}}$ or significantly above it.

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